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Spacecraft/Surface Charging (SCC):

- SCC Theory & Mitigation
- Detect Subsurface Defects
- Find ESD Initiation Point

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Objectives:

To talk about specific SCC issues

1. Prevent ESD* (by *Dissipating Surface Charge*)
- Spacecraft/Surface Charging: A Brief Tutorial
- Introducing the "Sweep Range"
- Redefining Surface Charge Mitigation Requirements

2. Detect Subsurface Defects
- Use Surface Charging as an Enabling Process

3. Find ESD Initiation Point
- Characterize Signature of ESD Current Transients
- Find ESD Initiation Point

* ElectroStatic Discharge

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PREVENT ESD

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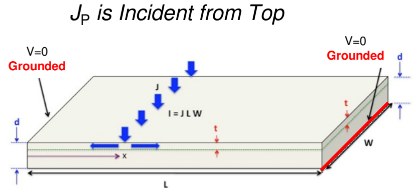
A Brief Tutorial on Spacecraft/Surface Charging

Environment:
Plasma Potential, $V_P = (kT/q)$
Net Plasma Current Density, J_P.
J_P is Incident from Top



Sample Topology:
Rectangular Dielectric Surface
Grounded at opposite ends
Thickness = d
Stopping Distance = t
Bulk Resistivity = ρ
Surface Resistivity = ρ/t

The incident current density*, J_P, will deposit charge on the exposed top surface.

The surface current, I, will flow through an average resistance, R/L, and "*feel*" an electric field, $E(x) = I\,(R/L) = -$ **Grad**[$V(x)$], that pushes surface charge into reference ground.

At the same time the incident current from above accumulates along the x-direction and creates a current gradient, **Grad**[$I(x)$] = $-$ $\boldsymbol{J}_P\ W$.

Nonconductive dielectric surfaces will retain more charge than conductive dielectric surfaces.

$$^{*}J_P = J\left(1 - e^{-(V_P - V(x))/V_P}\right) = J\left(1 - \left(V(x)/V_P\right)\right)$$

Defining <u>Conducive</u> and ***<u>Nonconductive</u>*** Dielectrics

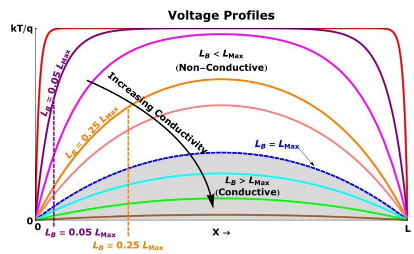
The equation to describe the voltage is:

$$V_B(x) = \left(\frac{kT}{q}\right)\left(1 - \frac{Cosh[(2x - L)/2L_B]}{Cosh[L/2L_B]}\right)$$

• The constant, L_B is called the "Sweep Range*."

• In terms of L_B, a dielectric surface is called "***<u>conductive</u>***" if the sweep range exceeds the maximum distance between any point on the surface and the nearest reference ground, L_{Max}, i.e., if $L_B > L_{Max}$.

• The surface is called "***<u>nonconductive</u>***" if the opposite is true, i.e., if $L_B < L_{Max}$.



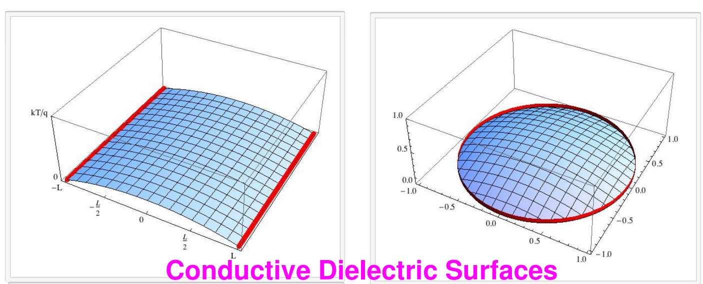
If $L_B >> L_{Max}$ (i.e., for highly "*conductive*" surfaces) then the voltage profile is well approximated by:

$$V_A(x) = \frac{1}{2} J\left(\frac{\rho}{t}\right) x(L - x)$$

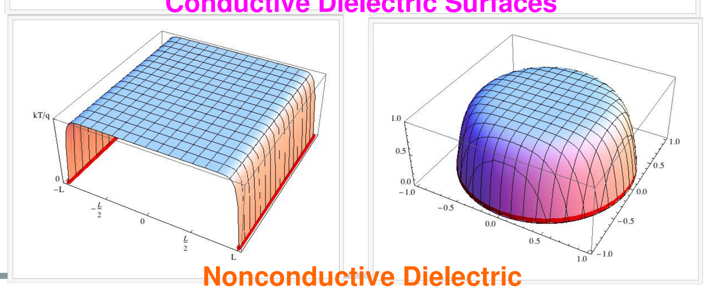
This expression could also be derived from Ohm's law.

* The sweep range is given by $L_B = \sqrt{(kT/q)/(\rho J/t)}$

3D Representation of Surface Voltage Profiles

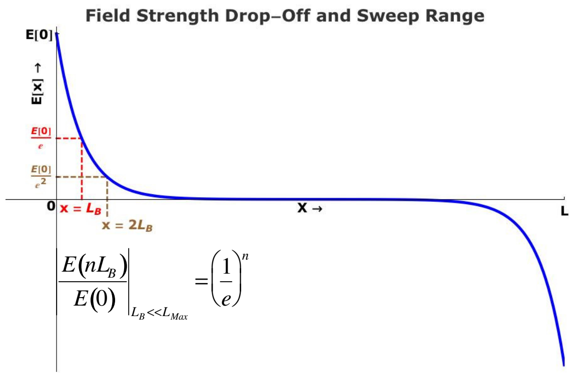


Conductive Dielectric Surfaces



Nonconductive Dielectric Surfaces

Interpretation of the Unit Sweep Range, L_B



$$\left.\frac{E(nL_B)}{E(0)}\right|_{L_B \ll L_{Max}} = \left(\frac{1}{e}\right)^n$$

"***Sweep Range***" is the characteristic distance over which the electric field strength across a ***nonconductive*** dielectric surface drops off by 1/e.

The Sweep Range can be thought of as a characteristic charge dissipation length or distance from reference ground.

From the expression for the surface voltage profile, it can be shown that for $L_B \ll L_{Max}$

$$\left|\frac{E(L_B)}{E(0)}\right| = \left|\frac{\nabla V(L_B)}{\nabla V(0)}\right| \approx \left(\frac{1}{e}\right)$$

In other words, ***the "Sweep Range" is the 2D analog of the 3D Debye length in plasma physics.***

Spacecraft/Surface Charge Mitigation: Conceptualizing Proper Grounding Methods

- ***Conventional*** Spacecraft/Surface Charge Mitigation requirements*
  - (*i*) *Specify surface resistivity, e.g.,* (ρ/t) ≤ 10^9 *Ω/Square*
  - (*ii*) Provide at least two ground wires, more for larger surfaces

- "***New***" Mitigation Requirement
  - ***Basic mitigation requirement: sweep charge off the entire surface, i.e., $L_B \geq L_{Max}$***
    - L_{Max} is the *maximum* distance from any point on the exposed dielectric surface to the nearest reference ground
  - ***From $L_B \geq L_{Max}$ the derived mitigation requirement is: (ρ/t) ≤ V_P / (J (L_{Max}^2))***
    - The surface resistivity, (ρ/t), is an *intrinsic property of the dielectric material*
    - L_{Max} depends on the *shape of the surface* and the *grounding configuration*
  - ***The new mitigation Requirement can be met either by***
    - Changing the surface resistivity, (ρ/t), or by
    - Changing the grounding configuration so as to make $L_{Max} \leq L_B$

* Ref.: Purvis, C. K., Garrett, H. B., Whittlesey, A. C., and Stevens, N. J., "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects," NASA Technical Paper 2361, 1984.

Illustrative Examples:

Recommended **Surface Resistivity Requirements**

$$\text{Sweep Range} = L_B = \sqrt{\frac{(kT/q)}{(\rho J/t)}}$$

$$\text{Surface Resistivity, } R_S = (\rho/t) \le V_P \Big/ \left(J\, L_{Max}^2\right)$$

GEO Orbits

V_P=20 kV L_{Max} = *L*/2 cm

J=1 nA/cm² L_{Max} = *R cm*

$$(\rho/t) \le \frac{2x10^{13}}{L_{Max}^2}\ \Omega/Sq.$$

MEO Orbits*

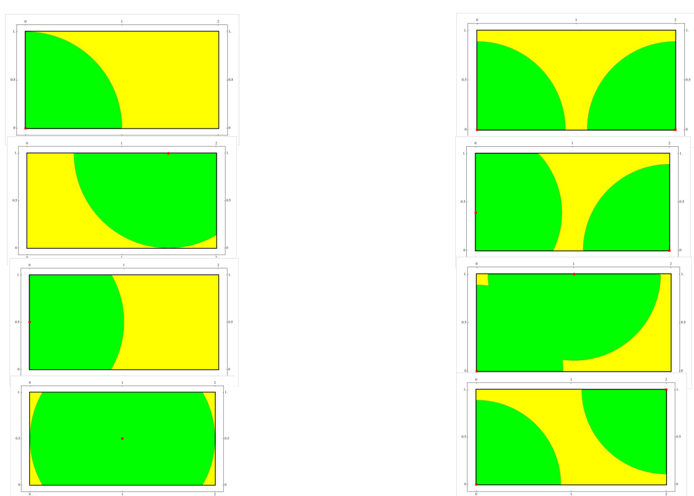
*V_P=2 kV** L_{Max} = *L*/2 cm

*J=10 nA/cm²** L_{Max} = *R cm*

$$(\rho/t) \le \frac{2x10^{11}}{L_{Max}^2}\ \Omega/Sq.$$

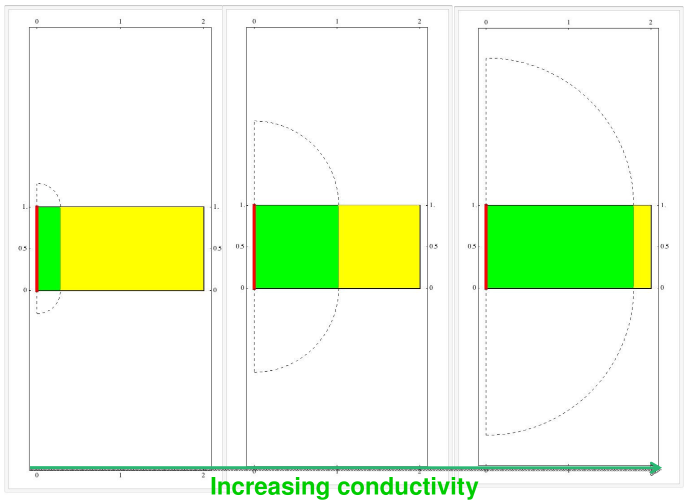
*** MEO Charging Environment is as yet ill defined***

Effectiveness of 1 vs. 2 ground wires

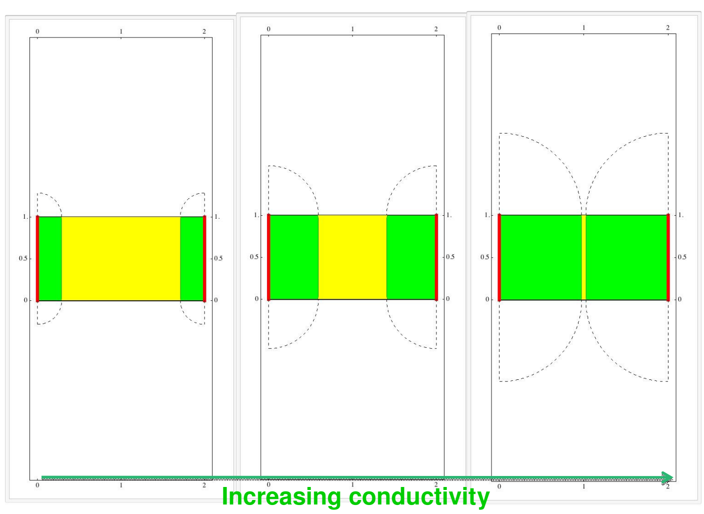


1 ground wire **2 ground wires**

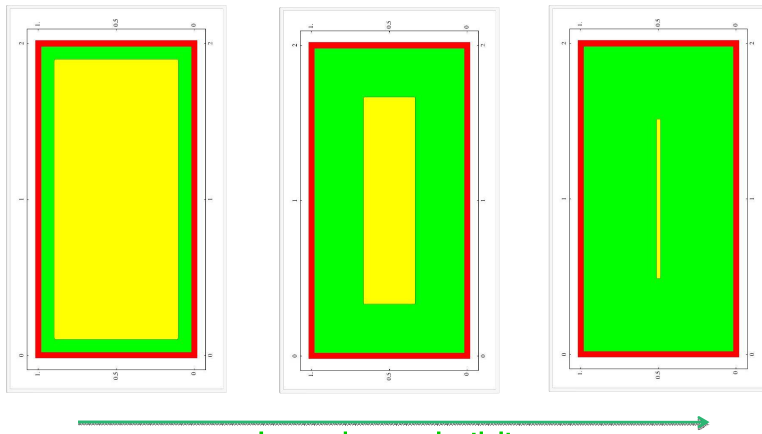
Effectiveness of One-Edge Grounding



Effectiveness of Two-Edge Grounding

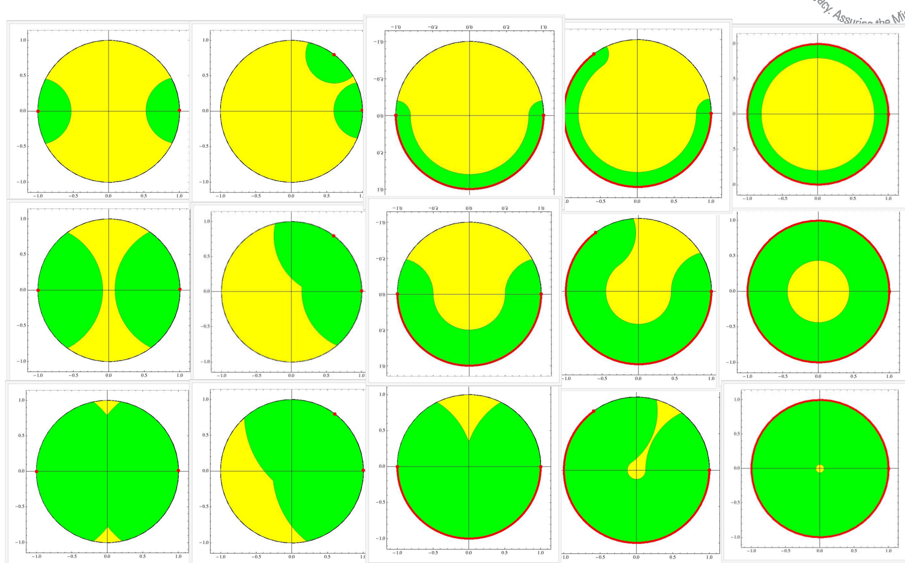


Effectiveness of Circumferential Grounding



Increasing conductivity

Grounding Effectiveness on Disks



Two ground points | Two ground points | 1/2 Circle Ground | 2/3 Circle Ground | Full Circle Ground

Recommended Mitigation Requirements

Fundamental Mitigation Requirement : $L_{Max} \le L_B$

Derived Mitigation Requirement : $\left(\rho/t\right) \le \frac{kT/q}{JL_{Max}^2}$

Sweep Range $= L_B = \sqrt{\frac{(kT/q)}{(\rho J/t)}}$

GEO Orbits

$V_P = 20\ kV; \quad L_{Max} = L/2$

$J = 1\ nA/cm^2; \quad L_{Max} = R$

(ρ/t)	10^8	10^9	10^{10}	10^{11}
L_B[GEO]	447 *cm*	141 *cm*	44.7*cm*	14.1*cm*

$$(\rho/t) = R_S \le \frac{2x10^{13}}{L_{Max}^2}\ \Omega/Sq.$$

MEO Orbits*

$V_P = 2\ kV; \quad L_{Max} = L/2$

$J = 10\ nA/cm^2; \quad L_{Max} = R$

(ρ/t)	10^8	10^9	10^{10}	10^{11}
L_B[MEO]	44.7*cm*	14.1*cm*	4.47*cm*	1.41*cm*

$$(\rho/t) = R_S \le \frac{2x10^{11}}{L_{Max}^2}\ \Omega/Sq.$$

** MEO Charging Environments are as yet ill defined*

How to Tailor GEO SCC Mitigation Requirements for MEO orbits

Summary from previous slide*:

$$R_S[MEO] = \left(\frac{1}{100}\right) R_S[GEO]$$

$$L_B[MEO] = \left(\frac{1}{10}\right) L_B[GEO]$$

Options:

- Change surface coating to reduce R_S ...... **"DIFFICULT"**
- Reconfigure grounding to reduce L_{Max} ...... **"EASY"**

**** MEO Charging Environment is as yet ill defined***

Intermediate Review

- We completed a brief tutorial on Spacecraft/Surface Charging
  - *We introduced the concept of the* ***Sweep Range, L_B***
  - *We explained the physical meaning of* L_B
  - *We defined "Conductive" and "Nonconductive" dielectrics in terms of* L_B
  - *We introduced the basic SCC Mitigation Requirement with reference to* L_B
  - *We introduced the derived SCC Mitigation Requirement*

- **Claim:** Using the concept of the Sweep Range *anyone* can tailor SCC Mitigation Requirements to prevent ESD (choose between two options), and demonstrate compliance

- Up to this point, we wanted to convince the reader that surface charging is "**bad**" for spacecraft: therefore, for all space programs we mandated SCC mitigation requirements to prevent ESD.

- Incidentally, for dielectric surface coatings, the purpose of SCC Mitigation is to limit offset voltages on scientific instruments, that are mounted on the coating, by specifying an upper limit for the bulk resistivity*. **Let us now look at the good side of surface charging.**

Surface Charging is an enabling process for detecting Subsurface Defects

*** Ref.: Albert Whttlesey, NASA JPL, personal communication.**

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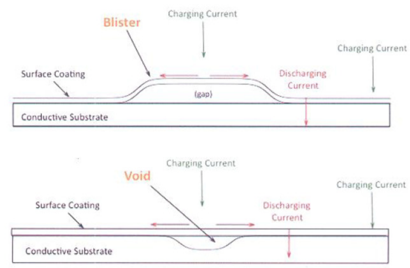
DETECT SUBSURFACE DEFECTS

A brief Tutorial on ES NDET* to Detect Surface Defects§

Definitions

- Blister
  - *The open space between a detached dielectric coating and a conductive substrate*
- Void
  - *The open space between a conductive substrate with a surface defect and a dielectric coating*



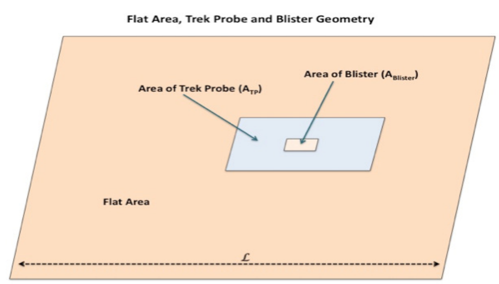
** ElectroStatic Non-Destructive Evaluation and Testing*

Surface voltages change measurably over defects or surface anomalies

§ **Patent Pending**

Measure Voltage Differences With a Non-Contact Volt Meter to Detect Defects

- A non-contact volt meter, e.g. a Trek Probe, measures the weighted **average** of the voltage over the probe area (typical probe area is 1 cm^2)
- Even for small defects, the voltage change can be high enough to be detected by a Trek Probe when it is moved across the defect area
- Measured voltage over probe area
- Voltage change observed by probe passing over defect



$$V_{TP} = \frac{A_{Defect}\langle V_{Defect}\rangle + (A_{TP} - A_{Defect})V_{Flat}}{A_{TP}}$$

$$\Delta V = V_{TP} - V_{Flat} = \left(\frac{A_{Defect}}{A_{TP}}\right)\left(\langle V_{Defect}\rangle - V_{Flat}\right)$$

Illustrative Examples: Demonstrate Ability to Detect Defects

$V_P = 20\ kVolts$ $\rho = 10^{11}\ \Omega.cm$ $V_{Flat} = \rho Jd = 25.4\ Volts$

$J = 10\ nA/cm^2$ $d = 10\ mils$ $V_{Noise} \approx 0.003\ Volts$

$A_{TP} = 1\ cm^2$ $t = 0.2\ mils$ $\Delta V = (V_{TP} - V_{Flat}) = A_{Defect}\left(\langle V_{Defect}\rangle - V_{Flat}\right)/A_{TP}$

Rectangular Defects

$L = 20\ mils$

$\langle V_{Defect}\rangle = (\rho J/t)L^2/12 = 423.3\ Volts$

$\Delta V = 1.027\ Volts >> V_{Noise}$

$$Signal/Noise = 1027/3 = 50.7\ dB$$

Circular Defects

$R = 10\ mils$

$\langle V_{Defect}\rangle = (\rho J/t)R^2/8 = 158.8\ Volts$

$\Delta V = 0.2703\ Volts >> V_{Noise}$

$$Signal/Noise = 270.3/3 = 39.1\ dB$$

There is more than adequate margin to detect even small defects

Locate the Origination Point of an ESD

- ESD is one of many on-orbit causes for mission degradation and/or mission failure. We have a need to know where a discharge occurred.
- If we are able to locate an ESD, then we can
  - *Improve operating procedures for existing satellites*
  - *Develop more effective diagnostics for anomaly resolution*
  - *Build more robust satellites in the future.*
- In the previous slides we showed we can harness surface charging and make it work for us. Likewise, we can harness the information in the signatures of current transients from brushfire discharges and make it work for us: the information will enable us to locate ESDs.
- **We present a novel technique to locate ESD on solar panels. The technique can be extended to locate the center of surface, i.e., brushfire discharges on other exposed surfaces.**

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Find ESD Initiation Point

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Agenda

Theory
- *We present the Theory of Surface Discharges*

ESD Transient Current Characterization
- *We identify useful characteristics of surface discharges*

Determining ESD Location
- *We use characteristic signatures of surface discharges to* detect the location of an ESD

Verification & Validation; Technology Demonstration
- *We apply our algorithm to published data on a test coupon to determine the location of an ESD*

Summary and Conclusions

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THEORY
Brush Fire Surface Discharge

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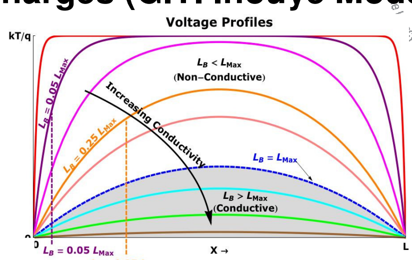
Brush Fire Surface Discharges (G.T. Inouye Model)

The theory of surface discharges is based on the brush fire discharge model of Dr. George T. Inouye[1]. For a rectangular surface of constant thickness, grounded at opposite ends along its entire width, the surface voltage profile is:

$$V_B(x) = \left(\frac{kT}{q}\right)\left(1 - \frac{Cosh\left[(2x-L)/2L_B\right]}{Cosh\left[L/2L_B\right]}\right)$$

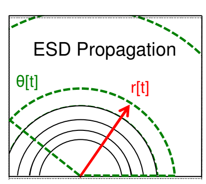
The constant, L_B is called the "Sweep Range".*



According to his model, a plasma cloud forms at the initiation point of an ESD. This cloud sweeps in a radial direction across a charged dielectric surface. Neutralization of surface charge occurs at the edge of the traveling plasma cloud. This creates a transient return current given by:

$$i(t) = \sigma_q\left(r[t]\ \theta[t]\right)\left(dr/dt\right)$$

where σ_q is the surface charge density and $\theta[t]$ is *origination point-dependent.*



Homogeneous Surface:

$$i(t) = \sigma_q\left(dr/dt\right)\ r[t]\ \theta[t]$$

Solar Power Panel:

$$i(t) = \sigma_q\left(dr/dt\right)\sum_{All\ cells}\left(r[t]\ \theta[t]\right)_{cell}$$

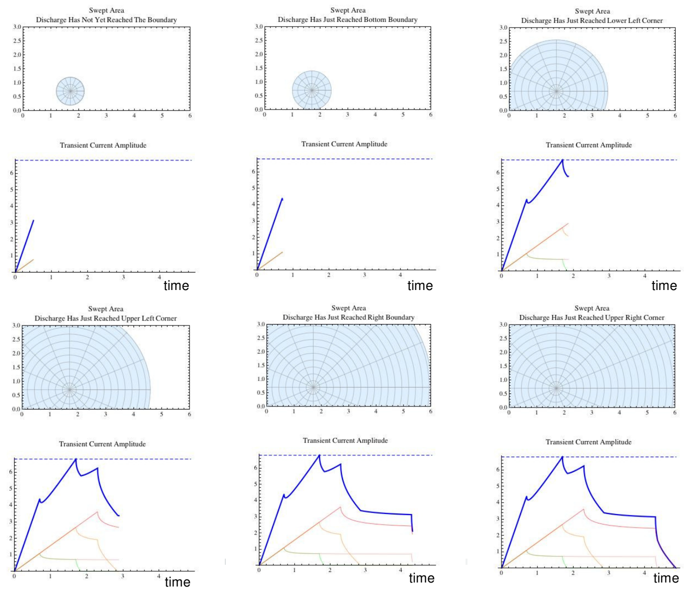
*Note that **r[t] θ[t]** is the total circular arc length that lies within the boundaries of the rectangle at time t:*

It depends on, and therefore can be used to determine, the origination point.

*The sweep range is given by $L_B = \sqrt{(kT/q)/(\rho J/t)}$

[1] G.T. Inouye, "Brushfire Arc Discharge Model," Spacecraft Charging Technology, 1980, NASA CP-2182, AFGL-TR-02770, 1981.

Time Progression of a Discharge



ESD TRANSIENT CHARACTERIZATION

Conventional ESD Transient Current Characterization

Transient Current from an ESD on a Solar Panel

$$i(t) = \sigma_q \frac{dr}{dt} \sum_{All\ cells} (r[t]\ \theta[t])_{Cell}$$

Rise Time

- ***Governed by Plasma Cloud Expansion Rate***

Fall Time

- ***Governed by Residual Charged Area at End of Pulse***

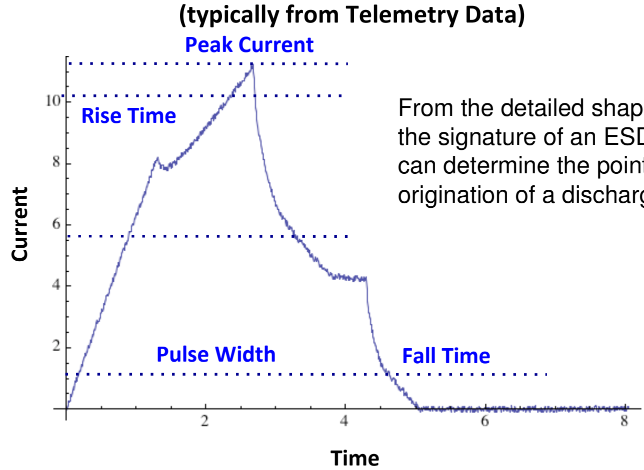
Pulse Width

- ***Governed by ESD Initiation Point and Area Size***

Peak Current

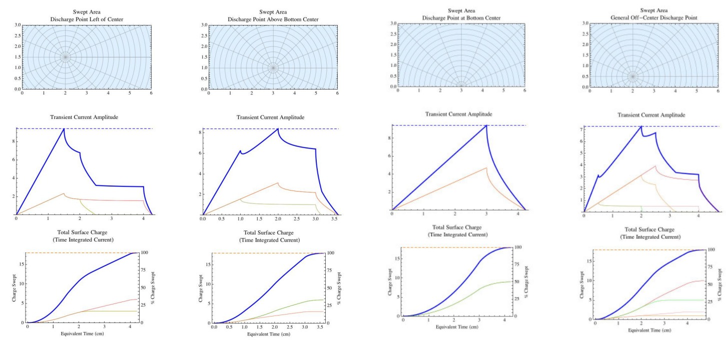
- ***Governed by ESD Initiation Point and Area Size***

Representative Signature of Measured Current Transient (typically from Telemetry Data)



From the detailed shape of the signature of an ESD we can determine the point of origination of a discharge.

The Signature of a Transient Current Depends on the Location of an ESD

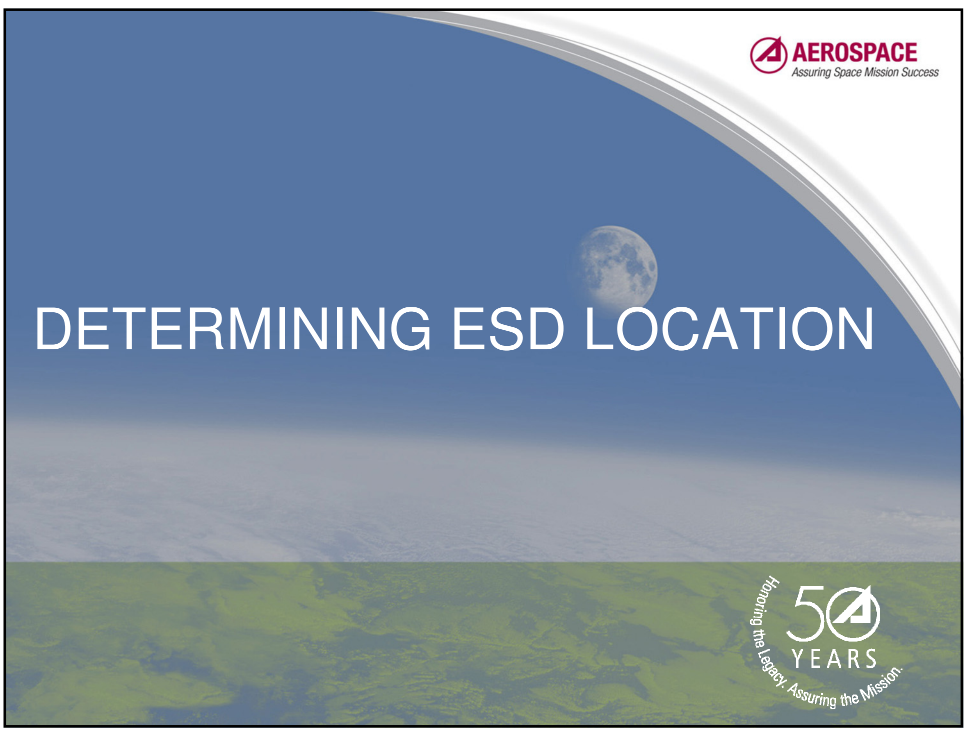


Read from beginning to end:

The location of the initiating ESD event determines what the signature of the transient current will look like.

Read from end to beginning:

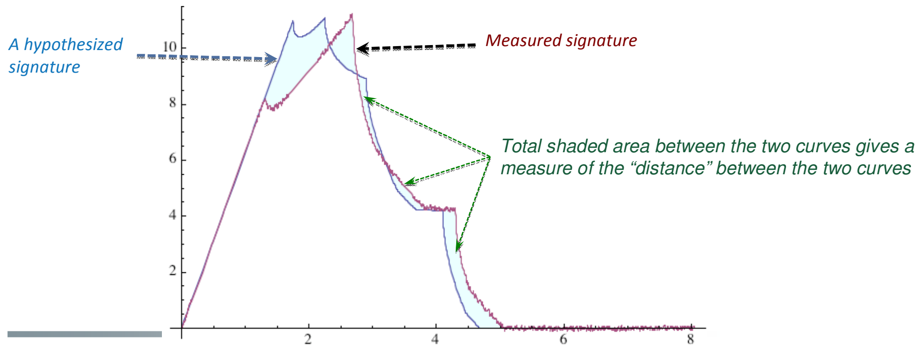
The signature of a transient current contains all the information about the location of the initiating ESD event.



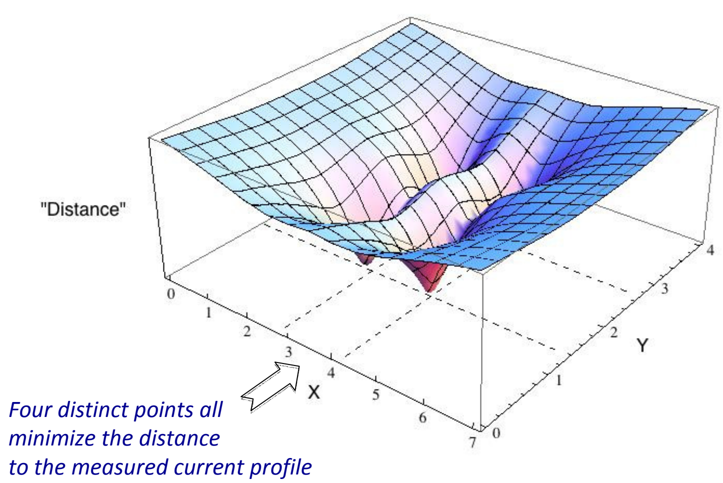
DETERMINING ESD LOCATION

Create a Distance Norm (or Metric) for the "Distance" between a Hypothesized Signature and a Measured Signature

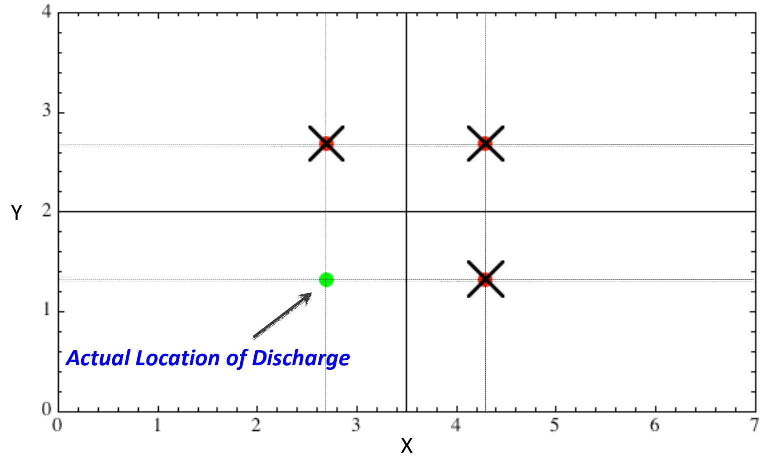
- We need a way to measure how "close" a measured signature is to a hypothesized signature that was pre-calculated and stored in a look-up table
- Use the area between the two curves as the basis for a Distance Norm or Metric. This area goes to zero when the hypothesized signature matches the measured signature



"Distance" (to measured current profile) vs. X and Y Exhibits Four–Fold Symmetry (for a Rectangular Region)

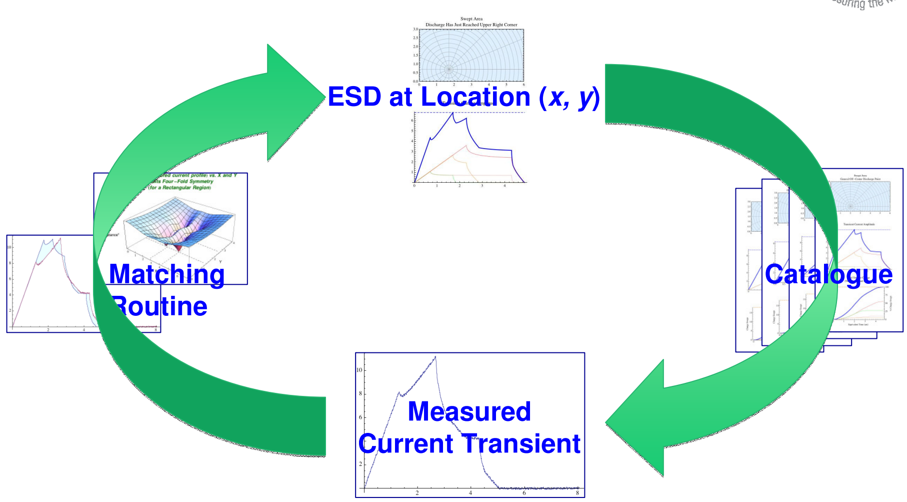


Possible/Candidate ESD Locations on a Surface with Inherent Four-Fold Symmetry



ESD location-ambiguities on panels with inherent symmetry can be resolved by measuring start-time differences between ESD current transients in separate wires.

ESD Detection and Location Methodology



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VERIFICATION & VALIDATION

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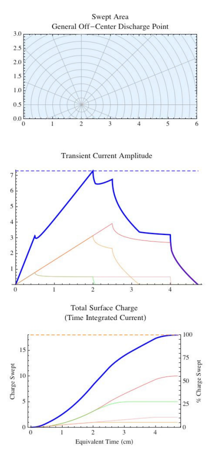
Steps to Extricate Location Information from the Signature of an ESD§



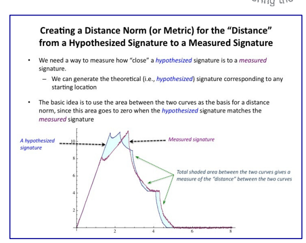
Construct a catalogue of panel-specific, origination-point-dependent signatures

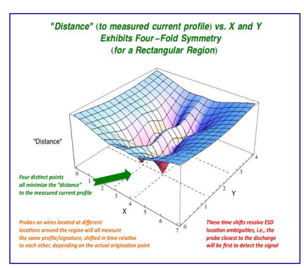
Reconstruct measured ESD signature

Compare signature with catalogue data

Determine/find minimum "Distance" to identify candidate ESD locations

Resolve inherent symmetry ambiguities

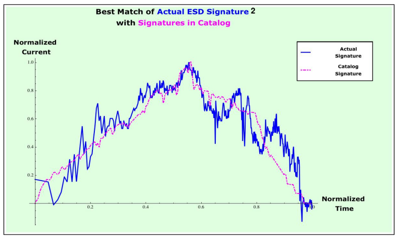




§ Patent applied for

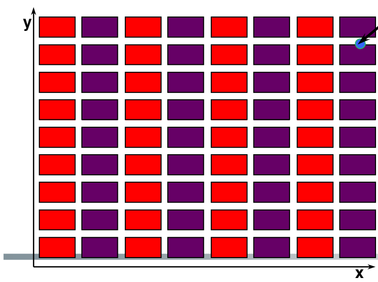
Technology Demonstration:

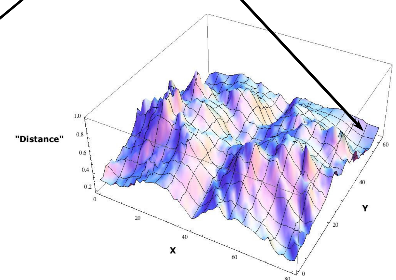
Compare measured signature[(2)] with cataloged signatures



- **"Distance" metric shows *approximate* four-fold symmetry**

- **Most likely ESD location identified**
  - **One of four possible symmetry points**





[(2)] Measured signature data from discharges on test coupons representing typical solar panels was provided by Dr. J. Pollard of The Aerospace Corporation.

Summary of ESD Detection & Location

- We discussed the propagation of a surface discharge across a dielectric surface. The theory is based on Dr. George T. Inouye's Brush Fire discharge model [1].

- The brush fire discharge model predicts transient current signatures that are characterized by the electrical properties of the dielectric material, by its size, its shape, *and by the location of the discharge*.

- Based on the notion that the signature of a transient current from an ESD contains hidden information about the origination point of the ESD, we developed a technique to locate ESD on solar panels.

- The method requires no additional space hardware, and it can be extended to locate surface discharges on other exposed surfaces.

[1] G.T. Inouye, "*Brushfire Arc Discharge Model,*" Spacecraft Charging Technology-1980, NASA CP-2182, AFGL-TR-02770, 1981.

Summary

Spacecraft Charging On Orbit Can Lead To Unwanted Results
To Prevent ESD we write SCC Mitigation Requirements in terms of Sweep Range and Grounding Configuration

On the ground Surface Charging is an Enabling Process
We can use Surface Charging for Subsurface Defect Detection

Brushfire/Surface Discharge is an Enabling Process
The information in Current Transients from a Brushfire Discharge can be used to locate the origination point of a Surface Discharge

Thank you for your attention…

Questions N.E.1?